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Abstract

The central objective of this research program was the development of methods for nonlinear distributed feedback control of various classes of fluid dynamic systems based on appropriate forms of the Navier-Stokes equations. We systematically synthesized practically-implementable (i.e., low-order) nonlinear feedback control algorithms that enforce the requested stability and performance specifications in the distributed parameter (infinite-dimensional) closed-loop system. We successfully implemented nonlinear low-order feedback control on several fluid dynamic systems including the Burgers' equation, the Korteweg-de-Vries Burgers equation, the Kuramoto-Sivashinsky equation and the two-dimensional channel flow. In the context of these studies, we systematically dealt with: a) the accurate numerical simulation of the distributed models describing the fluid dynamic systems, b) the derivation of low-order approximations of these distributed models, and c) the synthesis of the controller (control algorithm and parameters) and the controller implementation (measurement sensor and control actuator type). Furthermore, we worked on the development of feedback control algorithms for fluid dynamic systems that can deal with the key practical issues of model uncertainty, time-delays in the measurement sensors and control actuators and constraints in the capacity of the control actuators. In addition, the issue of selection of optimal locations of the control actuators and measurement sensors was studied, and insights and fundamental understanding on the nature of the feedback control problem for fluid dynamic systems were provided.

In addition to our research on nonlinear feedback control of the aforementioned fluid dynamic systems, we pursued research on active feedback control of two-dimensional flow over a plat plate for frictional drag reduction using blowing and shear stress measurements. This part of our research was carried out in collaboration with the flow control group of Dr. Siva Banda at the Air Force Research Lab of the Wright Patterson Air Force Base. To this end, two graduate students of our group, James Baker and Prasenjit Ray, who were involved in this project visited Wright Patterson Air Force Base for three months in the summer of 2000 and 2001. The PI also visited repeatedly Wright Patterson over the last two years. The objective of this interaction has been to focus our research efforts on problems that are important to the Air Force goals and transfer the results of our research (codes for simulation of flows, order reduction and controller design algorithms and codes) to the Air Force Research Lab, and potentially have the opportunity for experimental implementation of flow control at Air Force Research Lab facilities.

NONLINEAR CONTROL OF FLUID FLOWS

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FINAL REPORT
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1 Abstract

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2 Research activities

The objective of this section is to provide a brief overview of the various projects carried out in the context of this grant.

2.1 Nonlinear control of fluid dynamic systems

We addressed [6] the nonlinear control of incompressible Newtonian fluid flows described by two-dimensional Navier-Stokes equations. We initially employed nonlinear Galerkin's method to derive low-order ordinary differential equation (ODE) models that accurately describe the dominant dynamics of the Navier-Stokes equations. These ODE models were subsequently used as the basis for the synthesis of low-order nonlinear output feedback controllers that enforce exponential stability in the closed-loop system. The developed control algorithms were successfully applied to the Burgers' equation [6], the Korteweg-de-Vries Burgers equation (shallow water waves) [5], the Kuramoto-Sivashinsky equation (wavy behavior of falling liquid films) [4, 12] and two-dimensional channel flow [6, 7, 8] for drag reduction. Extensive simulations of the appropriate Navier-Stokes equations describing the above fluid flows under the proposed nonlinear control algorithms were performed in order to evaluate their performance and robustness properties.

2.2 Control of dissipative PDE systems with actuator saturation

We developed a general framework for the analysis and control of dissipative partial differential equation (PDE) systems with manipulated input constraints [13]. Initially, a nonlinear model reduction scheme based on Galerkin's method is employed for the derivation of finite-dimensional ODE systems that yield solutions very close to those of the PDE system. These ODE systems are then used as the basis for the explicit construction, via Lyapunov techniques, of bounded nonlinear state and output feedback controllers that enforce stability and reference-input tracking in the presence of input constraints and provide, at the same time, an explicit characterization of the limitations imposed by input constraints on the admissible locations of control actuators that can be used to guarantee closed-loop stability. Precise conditions that guarantee stability of the closed-loop PDE system in the presence of input constraints are provided. The proposed analysis and controller synthesis results were used to stabilize an unstable steady-state of a diffusion-reaction process and the zero solution of the Kuramoto-Sivashinsky equation for a value of the instability parameter for which this solution is unstable.

2.3 Optimal actuator and sensor placement for spatially distributed systems

We proposed [1, 2] a methodology for the integration of nonlinear output feedback control with optimal placement of control actuators and measurement sensors for transport-reaction processes described by a broad class of quasi-linear parabolic PDEs. Given a class of stabilizing nonlinear state feedback controllers which were derived on the basis of finite-dimensional approximations of the PDE, the optimal actuator location problem was formulated as the one of minimizing a meaningful cost

functional that includes penalty on the response of the closed-loop system and the control action and was solved by using standard unconstrained optimization techniques. Then, under the assumption that the number of measurement sensors is equal to the number of slow modes, estimates for the states of the approximate finite-dimensional model from the measurements were computed and used to derive nonlinear output feedback controllers. The optimal location of the measurement sensors was computed by minimizing a cost function of the estimation error in the closed-loop infinite-dimensional system. It was established that the proposed output feedback controllers enforce stability in the closed-loop infinite-dimensional system and that the solution to the optimal actuator/sensor problem, which is obtained on the basis of the closed-loop finite-dimensional system, is near-optimal in the sense that it approaches the optimal solution for the infinite-dimensional system as the separation of the slow and fast eigenmodes increases. The proposed methodology was successfully applied to two representative transport-reaction processes and the Kuramoto-Sivashinsky equation [14] and extended to transport-reaction processes with uncertainty [3].

2.4 Control of flow over flat plate for drag reduction

We also considered two-dimensional incompressible Newtonian fluid flow over a flat plate and studied the problem of frictional drag reduction on the plate using active feedback control [9]. Several alternative control configurations, including both pointwise and spatially uniform control actuation and sensing, were developed and tested through computer simulations. All control configurations use wall shear stress measurements and apply blowing/suction type of control actuation to reduce the frictional drag exerted on the plate. The simulation results indicated that the use of active feedback control, which employs reasonable control effort, can significantly reduce the frictional drag exerted along the plate compared to the open-loop values.

3 Personnel Supported

Funds were used to provide one month of summer salary for the PI and partially support four graduate students Antonios Armaou (Graduated with Ph.D. in Spring 2001), Charalambos Antoniades (Graduated with Ph.D. in Fall 2000), James Baker (Graduated with M.S. in Spring 2001) and Prasenjit Ray (currently pursuing his Ph.D. at UCLA). Funds were also used to travel to the American Control Conference to present results of this work and to visit the Dynamics and Control group at the Wright Patterson Air Force Base.

4 Interactions

In the context of this research project, we collaborated with the flow control group of Dr. Siva Banda at the Air Force Research Lab of the Wright Patterson Air Force Base. The point of contact at Wright Patterson Air Force Base is: Dr. James Myatt, Phone: (937)-255-8491 and Email:James.Myatt@va.afrl.af.mil. The objective of this interaction has been to focus our research efforts on problems that are important to the Air Force goals and transfer the results of our research (codes for simulation of flows, order reduction and controller design algorithms and codes) to the Air Force Research Lab, and potentially have the opportunity for experimental implementation

of flow control at Air Force Research Lab facilities. To further pursue this interaction, two graduate students of our group, James Baker and Prasenjit Ray, who were involved in this project visited Wright Patterson Air Force Base for three months in the summer of 2000 and 2001. The PI also visited repeatedly Wright Patterson over the last two years.

5 Transitions

Performer: Professor Panagiotis D. Christofides, UCLA, 310-794-1015. The work was performed by graduate students James Baker and Prasenjit Ray.
Customer: Wright Patterson Air Force Base, Dynamics and Control Group, Dr. Siva Banda, (937)-255-8677. The collaboration is with the flow control group. Leader: Dr. James Myatt, (937)-255-8491.
Result: Development of simulation codes and control algorithms for flow over a flat plate. The codes were written using the finite-element software FEMLAB and were transferred to the flow control group.
Application/Military Utility: Drag reduction/separation control in air vehicles.

6 Honors/Awards

In the period of this grant, the PI received the following distinctions:

- ONR Young Investigator Award, 2001.
- Article [10] published in the Perspectives Column and appeared in the Cover of AIChE Journal, March 2001.
- Inclusion in the Who's Who in America, 56th Edition, 2002.
- Early Promotion to Associate Professor with tenure.
- O. Hugo Schuck Best Paper Award (with Antonios Armaou), American Automatic Control Council, 2000.
- Plenary talk in the Process Systems Engineering 2000 Conference.
- AIChE Journal Article of the Month, February 2000.

In addition, Antonios Armaou received the Outstanding PhD in Chemical Engineering Award in 2001 for his doctoral thesis and James Baker received the Outstanding MS in Chemical Engineering Award in 2001 for his masters thesis. Finally, a doctoral student of our group who worked on the AFOSR project, Dr. Antonios Armaou, accepted an offer to join as Assistant Professor, tenure track, the faculty in the Department of Chemical Engineering at the Pennsylvania State University.

7 Publications

Up to this point, the research carried out under our current AFOSR grant has led to twelve journal publications and seven conference proceedings papers. More than

fifteen presentations at conferences and universities including results of this research have also been given by the PI. In addition, using AFOSR support the PI completed a research monograph on nonlinear and robust control of partial differential equation systems [11]. The major publications are listed below:

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